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Optical properties of InGaAsN/GaAs quantum well and quantum dot structures for longwavelength emission

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Introduction

Lasers emitting in the wavelength range near 1.3 μm are the key components of the fiber optic communication systems. Currently these are fabricated using InGaAsP or InGaAlAs heterostructures on InP substrates. However, these devices have some essential disadvantages: poor temperature stability due to the small conduction band offset [1], low thermal conductivity and difficulties in fabricating highly reflecting distributed Bragg reflectors (DBR) due to the low difference of the refractive indices. The last disadvantages are particularly important for vertical cavity surface emitting lasers (VCSELs). This stimulates attempts to fabricate high quality 1.3 μm lasers on GaAs substrates. The best results are obtained using InGaAs/GaAs self assembled quantum dots [2, 3] and using InGaAsN alloy insertions in a GaAs matrix [4–7].

An addition of several percents of Nitrogen into (In)GaAs alloy was shown to result to the strong bandgap decrease due to the large bandgap bowing parameter in the GaAs–GaN system [4]. The insertion of N into InGaAs also leads to a strain compensation, and the growth of $In_xGa_{1-x}N_yAs_{1-y}$ layers lattice matched to GaAs substrate is possible for $x \sim 3y$. A high temperature stability of the threshold current density in the lasers based on this system was predicted theoretically due to the large conduction band offset in the InGaAsN/GaAs heterostructures [4]. Fabrication of the surface–emitting lasers is possible using well developed technology of AlGaAs/GaAs DBR.

1.3 μm lasers based on InGaAsN insertions in GaAs have been fabricated by several research groups [5, 6]. The CW emission at room temperature with a low threshold current density of 400 A/cm^2 and high output power of 2.7 W were reported [6]. The vertical cavity surface emitting laser (VCSEL) emitting at 1.18 μm was also reported [7].

The main problem in the InGaAsN epitaxy is a large difference in the atom sizes of As and N, which makes difficult the uniform alloy formation. The incorporation of large amount of N into GaAs leads to a phase separation [8]. Even in the case of low N contents, the main problem in the growth of InGaAsN/GaAs heterostructures is a degradation of the material quality when Nitrogen concentration is increased [9]. In molecular beam epitaxy (MBE) one of the reasons of this is the surface quality degradation due to the high energy ions originating from plasma nitrogen source which is necessary to obtain the active nitrogen pieces [10]. So, the optimization of growth conditions is required to achieve an efficient 1.3 μm emission and to improve the laser performance. In this work we investigate the optical properties of (In)GaAsN/GaAs heterostructures grown by MBE, and show the possibility to realize the 1.3 μm emission using the different structure parameters.

1. Experiment

The investigated structures were grown by MBE on GaAs semi–insulating substrates using standard solid state cells of the group III elements. High volume solid state cell with a cracking area was used to create the As molecules. The active Nitrogen radicals were created by gas Nitrogen flux through the standard radio frequency plasma source. The plasma source power was changed in the range of 75–150 W. Two types of samples were grown: the thick (0.2 μm) GaAsN layers and InGaAsN quantum wells, placed in the center of 0.2 μm GaAs layer confined from the both sides by AlAs/GaAs superlattices. The growth temperature was 500°C for N–containing layers. Photoluminescence (PL) was excited by an Ar^+ laser ($\lambda \sim 514.5$ nm, 100 W/cm^2) and detected by a cooled Ge photodiode. Transmission electron microscopy (TEM) studies were carried out in a Philips EM 420 microscope operated at 100 kV.

2. Results and discussion

First, the Nitrogen incorporation efficiency in the GaAsN layers was studied. In Fig. 1 the results of x–ray diffraction measurements are shown for the samples grown at the different growth rates. The plasma source power was 75 W for both samples. To estimate Nitrogen content in the layers we used the method described in [11] and the elastic constants values from [12]. One can see that the lower growth rate leads to an increase in the N mole fraction in the layer. Moreover, Nitrogen incorporation rate $S_N = V_{gr} \times [N]$, where V_{gr} is layer growth rate, [N] is Nitrogen content in the layer, remains almost constant with growth rate variation. These data are in good agreement with the dependencies reported in [13], where it was also shown that N incorporation efficiency is independent on the growth rate.

Next, we investigated the samples with InGaAsN/GaAs insertions. The data obtained by x-ray diffraction were used to estimate the N concentration in these samples. In Fig. 2 the PL spectra of the samples with $In_{0.25}Ga_{0.75}AsN$ insertions are shown. One can see that the increase of the plasma source power from 0 to 75 W leads to the PL line redshift of ~80 meV. Assuming that the N content in GaAsN and InGaAsN at the same source power are also similar, we estimate that this shift corresponds to [N] $\sim 0.5\%$. Thus, using a linear approximation, we obtain the dependence of PL maximum on the N content with the line slope of 160 meV/(%). This result is in good agreement with the data reported in [8]. Thus, we estimate the maximum N content in our samples as ~1.3%.

We investigated the optical properties of InGaAsN–GaAs structures with a different In

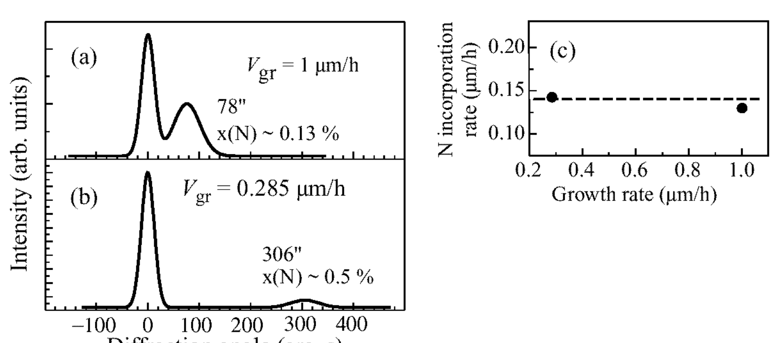

Fig. 1. (a), (b) Rocking curves for GaAsN layers grown at the different growth rates with plasma source power of 75 W. (c) Dependence of N incorporation rate on the growth rate.

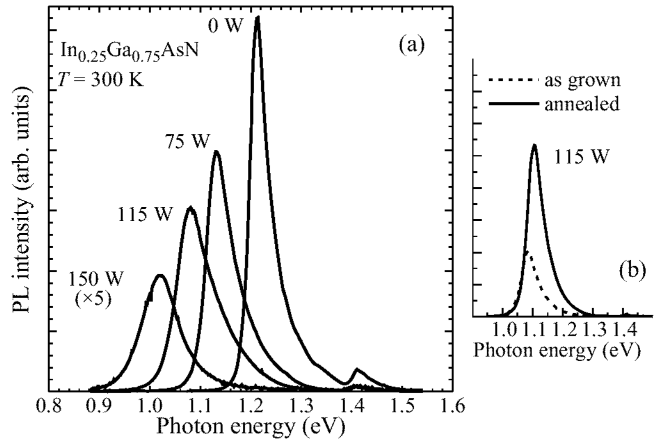

Fig. 2. (a) PL spectra of InGaAsN QWs grown at the different plasma source power (marked near the spectra). (b) PL spectra of the (115 W) sample before and after postgrowth annealing (700°C).

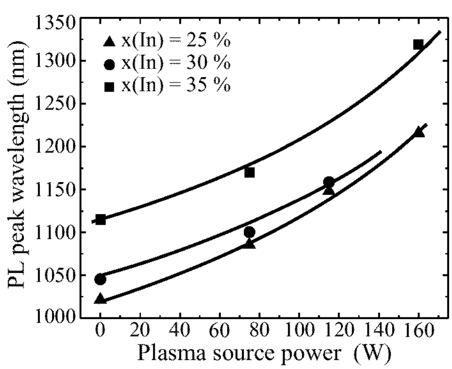

Fig. 3. PL peak positions at room temperature for samples with different In and N concentration in QW.

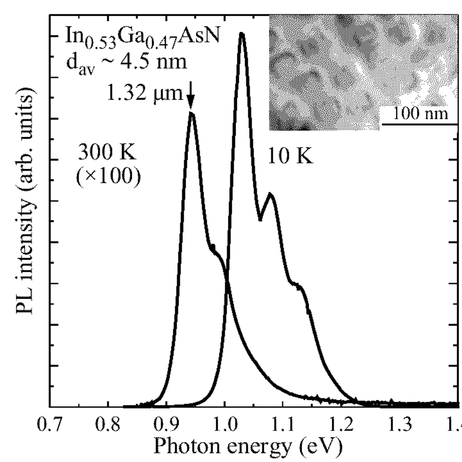

Fig. 4. PL spectra for the sample with InGaAsN QDs. In the inset — the plane-view TEM image of this sample.

and N composition. The PL peak positions are shown in Fig. 3. For small Indium and Nitrogen composition PL emission looks similar to emission in InGaAs–GaAs quantum well (QW) structures. For higher Indium and Nitrogen content PL broadens significantly. The increase of plasma source power leads to a continuous PL redshift at any given In composition in the InGaAsN. At the maximum power of 150 W and In content of 35%, the PL line at 1.32 μm was observed. The increase in N concentration also leads to a significant PL intensity decrease, which is typical for InGaAsN layers. The improvement of PL intensity of InGaAsN QWs is possible by using high temperature postgrowth annealing [10]. We investigated the annealing effect on the optical properties of our structures. The annealing was carried out in the growth chamber under As flux. The annealing at 650°C (1 hour) did not change neither PL intensity, nor peak position. Using the 700°C anneal leads to the 3 times increase in integral PL intensity, while the corresponding PL blueshift was rather small (20–25 meV for different structures) (see Fig. 2(b)). Thus, the postgrowth annealing gives a possibility to improve the quality of the structures without significant

changes in their electronic spectrum.

We note that to get 1.3 μm emission one needs to use both higher Indium and Nitrogen compositions. From the point of view of PL lineshape and linewidth the properties of the samples resemble PL properties of QD-like structures. We investigated PL in InGaAsN samples with higher In composition of 53%. TEM images show that dense array of rather large (lateral size (23 nm) QDs is formed in the structure (see inset in Fig. 4.) The PL spectra of this structure is shown in Fig. 4. The 3D localization is confirmed by the fact that the PL linewidth does not change with the temperature variation from 10 to 300 K (FWHM $\approx$ 45 meV). We note that PL wavelength in this sample is 1.32 μm, in spite of rather small N concentration in this sample. Thus, the significant redshift thus can be attributed to both QD formation and Nitrogen incorporation. Longwavelength emission from InGaAsN structures using relatively small N concentrations may lead to a significant increase in the PL intensity and, hence, to an improvement of the laser performance.

To conclude, we investigated the optical properties of heterostructures with InGaAsN/GaAs QW–like and QD–like insertions. GaAsN and InGaAsN layers with relatively high nitrogen content (more than 1%) were grown. The long wavelength emission up to 1.32 μm at room temperature was realized. TEM and optical studies confirm formation of quantum dots for the case of higher indium concentrations.

Acknowledgements

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